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Magellan Radar Special Flight Experiments

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Special radar experiments were conducted by the Magellan spacecraft to explore resolution enhancement, stereo imaging, and effects of radar polarization. These are described herein, along with an overview of the Magellan mission to Venus and a summary of the spacecraft systems and capabilities. Unusual commanding constraints are discussed, and a summary of experiment results is given.

Introduction

The geologic nature of Venus is of interest to scientists because of its similarities to Earth. Observing Venus optically is not possible, because the surface is obstructed by a thick cloud cover (Fig. 1). Radar techniques have been used successfully to penetrate this cloud cover by ground-based observations from Arecibo, Puerto Rico, and Goldstone, California, and by space-borne observations from the Pioneer Venus Orbiter and the Soviet Venera spacecraft.[1-4]

The Magellan mission,[5] commissioned by NASA at the Jet Propulsion Laboratory (JPL), set out to use radar techniques to map Venus on a global scale. The Magellan spacecraft (Fig. 2) arrived at Venus in August 1990 and by January 1992 had mapped the planet for two complete revolutions of Venus or "cycles," each of which lasted 243 Earth days.

Cycle 1, from September 1990 to May 1991, concentrated on mapping the surface lying between the north pole and the mid-latitudes. During this time, images were acquired looking from various angles, but always to the left of nadir as seen looking along the velocity vector.

Cycle 2, from May 1991 to January 1992, concentrated on mapping from the mid-latitudes to the south pole while pointing to the right of the spacecraft. Targets were observed from the opposite side to better interpret the data taken in cycle 1.

In addition to these two major data collection modes, four special flight experiments were performed to validate mapping concepts for future mission cycles. These experiments explored resolution enhancement, stereo imaging, and effects of radar polarization. This paper addresses the goals of these experiments, how they were executed, and their results.

Magellan Spacecraft System

Spacecraft

The major components of the Magellan spacecraft are shown in Fig. 3.

The high-gain antenna (HGA) is 3.7 m across and is used both for transmission of data to Earth and for the radar. The spacecraft is equipped with two other communication antennas: a low-gain antenna (LGA) mounted atop the HGA and a medium-gain antenna (MGA) mounted to the side of the spacecraft. A radar altimeter antenna (ALTA) is mounted to the side of the HGA and is used for measuring the altitude of the terrain over which the spacecraft passes.[6]

The spacecraft is three-axis stabilized. Attitude control is commanded from two redundant computers located in the bus section of the spacecraft and is maintained through three orthogonal reaction wheels and by means of hydrazine jets.[7] A star scanner is used to preserve attitude knowledge.

Fig. 1 Venus photograph taken from Mariner 10 flyby in 1973.

Power is provided through use of solar panels, and the spacecraft is equipped with two nickel-cadmium storage batteries. Commanding is achieved through two redundant computers also located in the bus. During mapping activities, engineering data at 1200 bits/s and radar data at 806 kbits/s are recorded on a tape recorder with a capacity of 1.8×10^9 bits.[8,9]

Radar System

The Magellan radar system comprises the onboard radar flight hardware, ground software for assembling radar commands, and a complex data processing system that creates images for interpretation by scientists. The primary radar sensor uses the HGA in a side-looking synthetic aperture radar (SAR) mode.[10,11] Figure 4 shows the data collection geometry for a series of synthetic aperture bursts. When the target and the radar are moving with respect to each other, a "larger-than-life" or "synthetic" aperture is created. If the phase and amplitude of the return signals are recorded, then an image may be generated having resolution equal to that of the synthetic aperture. On Magellan, the same hardware that creates SAR bursts is used for altimetry and radiometry data collection, interspersed with the SAR data.

With regard to the planning and uplink of radar commands, the radar mapping sequencing software (RMSS) is a set of

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computer programs that generates a time-sequenced table of radar control parameters and spacecraft attitude pointing commands. These tables are combined with overall spacecraft sequencing instructions and transmitted to the Magellan spacecraft to command the spacecraft and radar activities over a two-week period.

RMSS also produces detailed predictions of radar performance for a given set of commands. Radar performance is defined to be acceptable when a number of constraints are met; the primary subset of such constraints is given in Table 1. These constraints must be held while maintaining a swath width of 20 km to ensure that no gores occur between mapping swaths so that a complete, seamless map may be produced.

Fig. 2 Magellan spacecraft leaving the Shuttle Atlantis cargo bay, May 4, 1989.

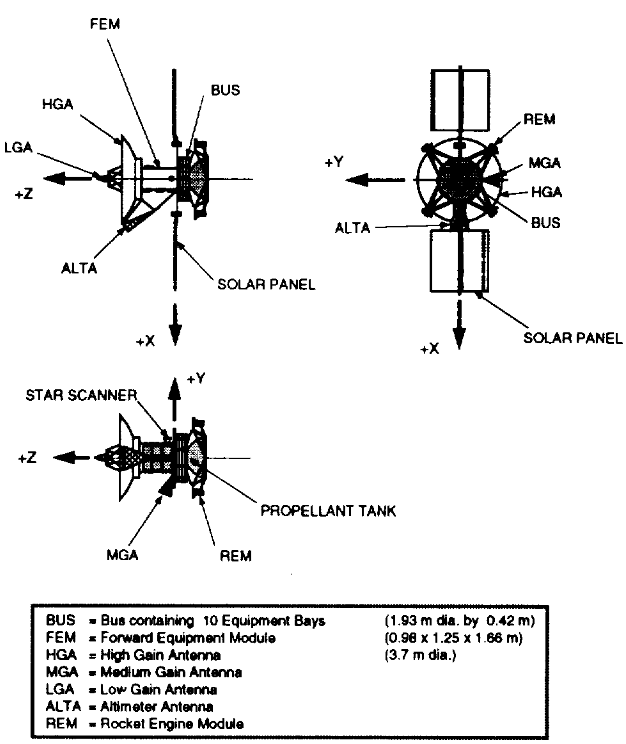

Fig. 3 Magellan spacecraft.

Table 1 SAR performance requirements

Signal-to-ambiguity ratio, db	≥15
Signal-to-thermal-noise ratio, db	≥8
Azimuth resolution, m	≤120
Range resolution, m	≤300
Number of raw looks	≥4

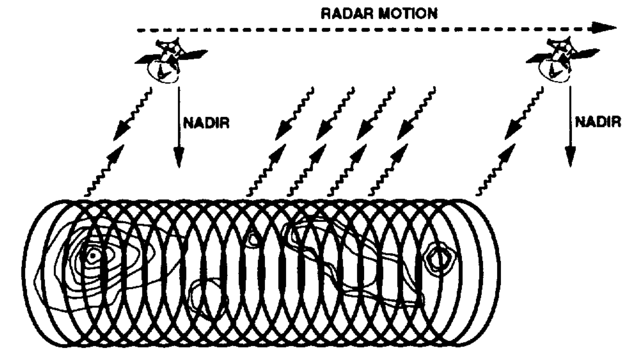

Fig. 4 Magellan radar data collection geometry for a series of synthetic aperture bursts.

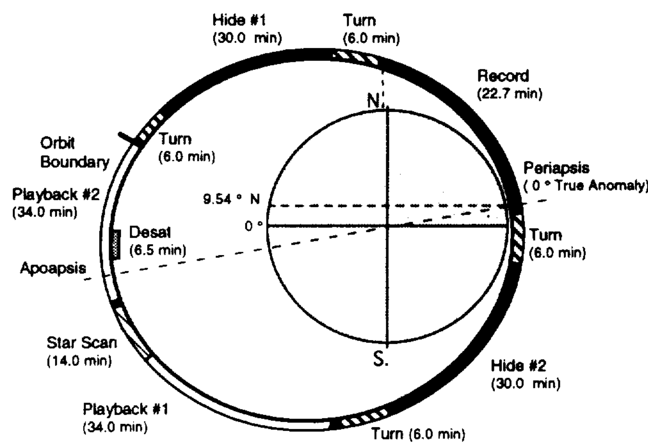

Fig. 5 Typical Magellan orbit. Orbiting clockwise in this figure, the spacecraft crosses the orbit boundary and begins a new orbit by turning the HGA to the hide attitude. After hiding, the HGA is turned to the planet surface, and radar imaging is recorded on the onboard tape recorder. After mapping is completed, the HGA is maneuvered for the second hide of the orbit. After this hide time is elapsed, the HGA is turned to earthpoint to begin playback of the first half of data collected. A star scan occurs near apoapsis, where attitude knowledge is updated. The second half of the radar data is then played back, and a new orbit begins. Example durations of these activities are shown in the figure.

Mapping Operations

Command sequences uplinked to Magellan cover operation for two weeks and are constructed on an orbit-by-orbit basis. The orbit period is approximately 3.25 h and apoapsis and periapsis altitudes are 8450 km and 250 km, respectively. Each orbit follows a profile similar to the one diagrammed schematically in Fig. 5. In the mapping phase of the orbit, the spacecraft points the HGA toward the planet to collect radar data. In the playback portions of the orbit, the HGA is pointed toward Earth.

When the orbits of Venus and Earth and the position of Magellan are such that the $-Z$ axis of the spacecraft is pointed at the Sun during data playback, time must be taken out of the orbit to control spacecraft temperatures. Magellan uses a strategy called "hiding" to protect sensitive onboard components from thermal extremes (Fig 6). In a hide maneu-

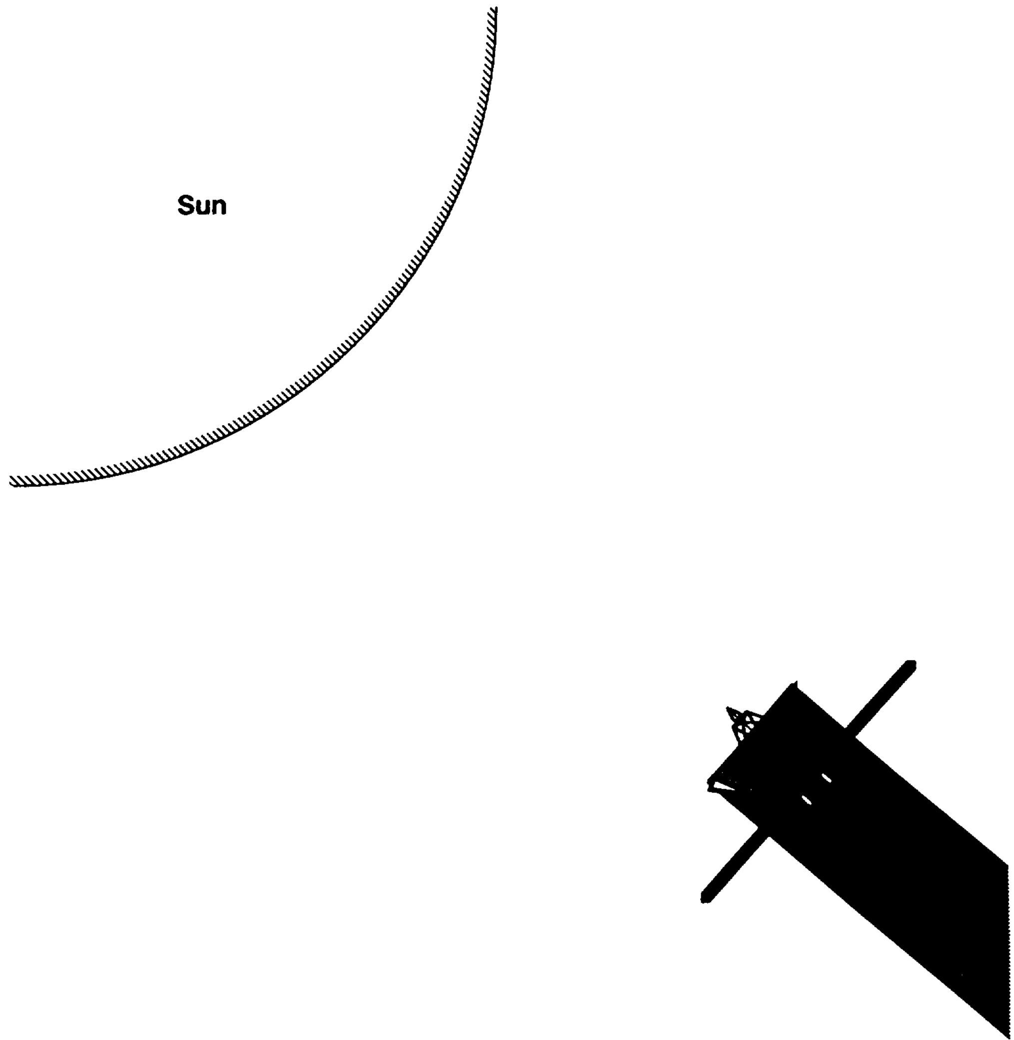

Fig. 6 Magellan "hides" from the sun behind the high-gain antenna to shade sensitive components from overheating.

ver, the spacecraft is maneuvered to an attitude where the spacecraft bus is shadowed from the sun by the HGA, hence hiding. In our current mapping configuration, the spacecraft performs two hides of equal length per orbit, with the hide durations being as long as required—up to 55 min each—to perform the needed cooling.

Several housekeeping functions are scheduled, such as a star calibration maneuver each orbit and a reaction wheel desaturation every fourth orbit. Command sequences are restricted in the amount of mapping data they can take by the amount of time left in the orbit period after time is allocated to these housekeeping functions and to data playback.[12]

Data Collected

The spacecraft "looks" to one side at a specific angle that is a function of the latitude over which the spacecraft is flying. The angle from nadir to where the antenna boresight is pointed is called the look angle. A corresponding measurement is the incidence angle, which is the angle from the radar line-of-sight to the line orthogonal to the planet surface (Fig. 7). The incidence-angle profile is the set of incidence angles commanded by the spacecraft relative to the latitudes over which the spacecraft flies. The incidence-angle profile for left-looking data collection taken during cycle 1 is shown in Fig. 8.

The special radar flight experiments, one in high-resolution imaging, two in stereo imaging, and one in polarimetry, were all designed to be combined with data taken in the first cycle of the mission. Care was given to when and where these experiments were carried out so that the targets imaged could be matched to data acquired in cycle 1.

The special radar flight experiments to be described in this paper occurred between July 1991 and January 1992 when

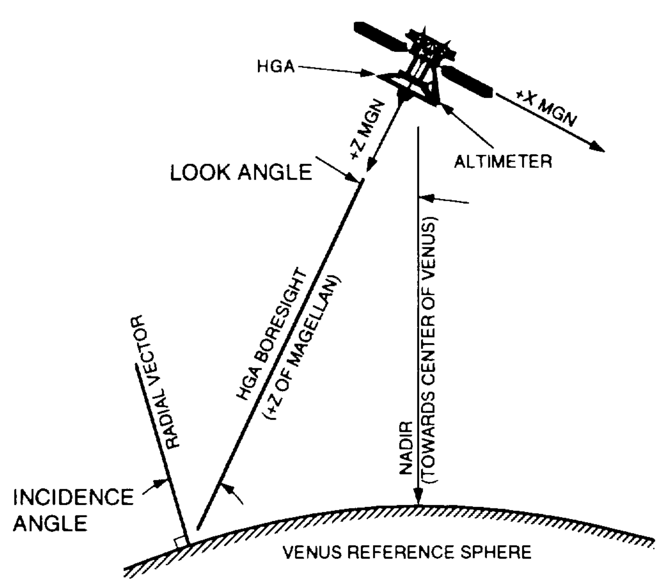

Fig. 7 Look and incidence angles (the spacecraft velocity is normal to the page).

right-looking data were being collected, following the constant incidence-angle profile shown in Fig. 9. These experiments were interspersed with this right-looking data collection.

High-Resolution Imaging Experiment

Image resolution is measured in two directions: the range or "cross-track" direction and the azimuth or "along-track" direction. Magellan's range resolution is a function only of the incidence angle that is being flown. The azimuth resolution, however, can be altered by choosing a different commanding strategy. In March 1991, Magellan science investigators indicated interest in achieving a higher image resolution. An experiment was devised to test this capability, specifically to limit the number of looks and thereby gain a resolution increase in the azimuth direction.

Description

It was decided that the best experiment would fix the incidence-angle profile, hence the range resolution, to that of data collected in cycle 1. By fixing the range resolution, the increased azimuth resolution and the associated smaller number of looks could be isolated and studied.

In the normal mode of operation, the azimuth resolution is maintained at 120 m. The high-resolution experiment at-

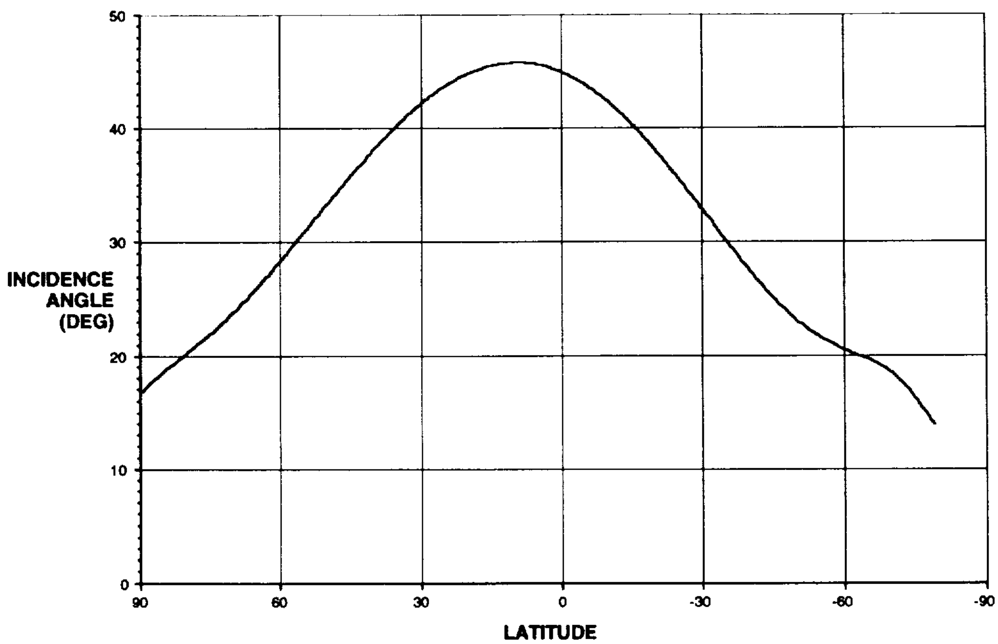

Fig. 8 Cycle 1 left-looking incidence-angle profile.

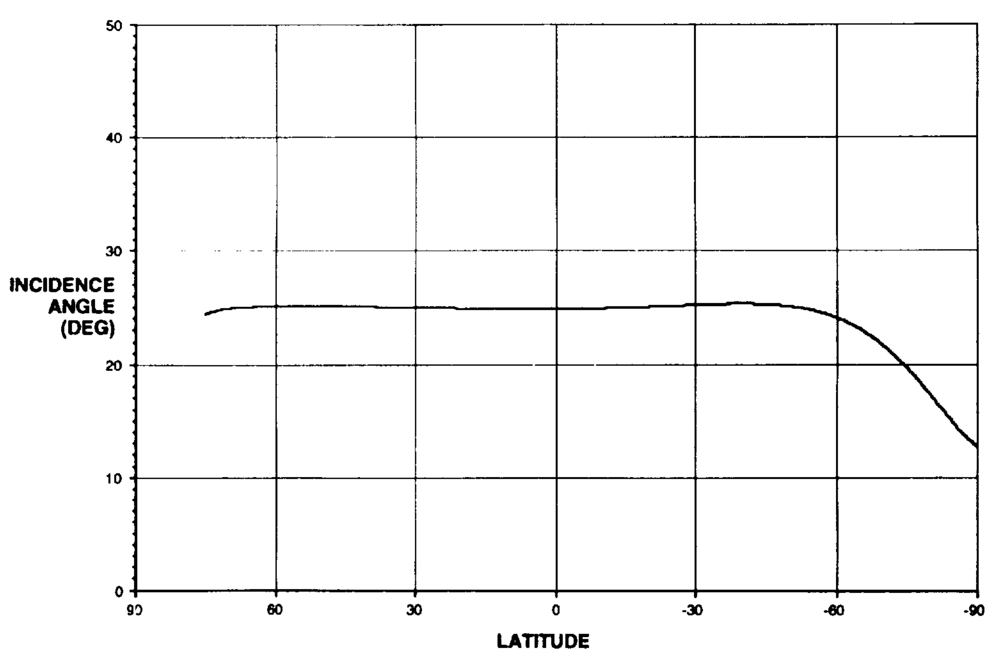

Fig. 9 Cycle 2 right-looking, constant 25-deg incidence-angle profile.

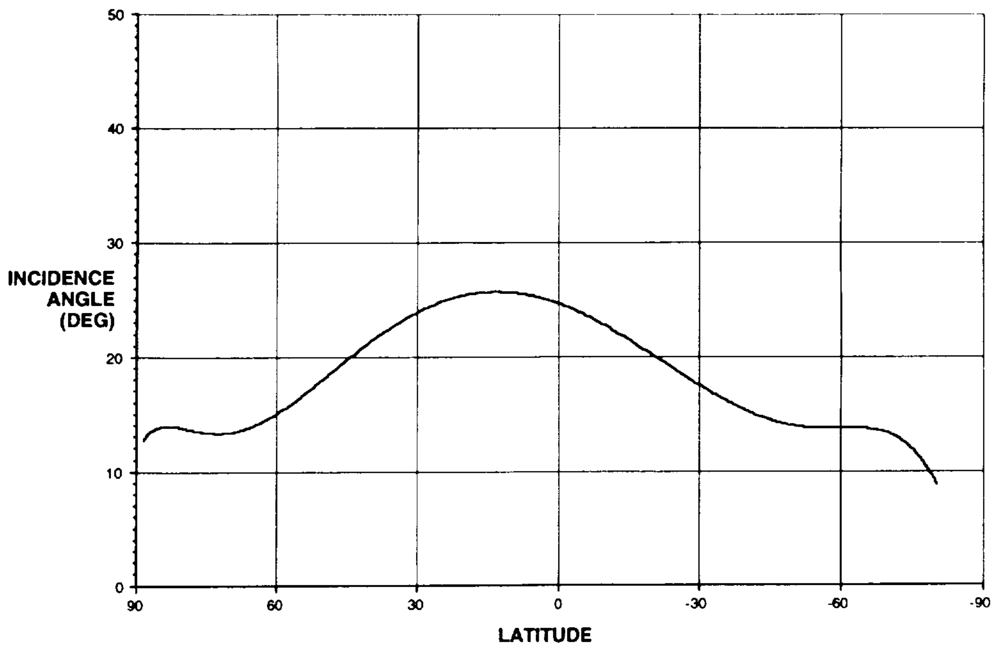

Fig. 10 Stereo experiment incidence-angle profile.

tempted to hold the azimuth resolution at double that, or 60 m, and was able to do so from 55°N to 30°S latitude. The performance predictions for this experiment showed signal-to-thermal-noise ratio able to hold its minimum requirement of 8 dB. The signal-to-ambiguity ratio, however, dips below 15 dB in this region to a low of 10 dB.

Execution

Because this experiment is configured almost exactly as nominal left-looking data collection, it was decided to piggyback the experiment at the end of the left-looking gap fill period resulting from superior conjunction during cycle 1 of the mission. Five orbits, 2582 to 2586, were allocated to this experiment immediately after the gap fill time. As the experiment followed the nominal left-looking attitude profile, implementation consisted of merely uplinking a new set of radar command parameters after completion of orbit 2581. The experiment was performed on July 12, 1991, without incident.

Results

The Magellan science community has concluded, in a report by Senske et al.,[13] that in general overall image appearance is improved, both in sharpness and definition of surface features. Because of the increase in speckle noise due to fewer looks in the high-resolution data, however, there is usually a tradeoff between information gained and lost from one data set to the other. Certain features show increased detail, whereas others are degraded and seen better in the nominal configuration. The report concluded that high-resolution imaging should be a secondary priority but that it would be most useful for imaging the high latitudes where resolution is at its worst currently. Magellan has long-range plans to circularize its orbit through the use of aerobraking,[14] and if this is done, the resolution improvement could be performed both in range and azimuth directions, to a total improvement of four to nine times the current image resolution.

Stereo Experiment

Interpretation of radar image data can be greatly aided by stereo viewing techniques. Stereo provides three-dimensional views of terrain for a better visual impression as to the actual terrain. Stereo also enables creation of highly accurate digital terrain models to judge terrain elevations. Stereo aids in interpretation of images taken at different incidence angles through "coregistration," a technique that enables scientists to interpret differences in images caused by shadowing and slope differences.

Stereo imaging requires two images of an area of terrain taken at different viewing angles (hence, incidence angles), which are then combined to create a three-dimensional picture of the region. Franz Leberl, a Magellan visiting scientist, proposed a stereo experiment where data would be collected at a new incidence-angle profile to be viewed together with images collected in cycle 1 to create stereo images.

Table 2 Stereo experiment desired incidence angle pairs

Imaging	Incidence angle, deg				
Cycle 1 nominal	45	30	20	16.5	13.5
Corresponding Stereo	25	16	14	11.5	9

Description

A new attitude profile was constructed according to Leberl's specifications (Table 2) to achieve incidence angles that correspond to the nominal incidence angles of cycle 1. This stereo incidence-angle profile is shown in Fig. 10. Performance predictions appeared quite strong, with thermal noise holding at 8 dB or better, ambiguities holding at 15 dB, and looks holding at four or better.

Magellan scientists also requested the flight team to switch to right-looking mapping immediately after this experiment. Switching to right-looking mapping caused the radar to sweep over the same terrain just imaged with the stereo left-looking profile (Fig. 11). By doing so, three views of the same terrain were achieved and allowed studies in radarclinometry, which uses shading in images to determine shape of terrain features.

Execution

Requirements for this experiment were to take data in a region where left-looking nominal coverage existed from cycle 1, as well as to cover latitudes such that at least one set of stereo angle pairs listed in Table 2 would be imaged. This presented a number of problems, since this experiment was

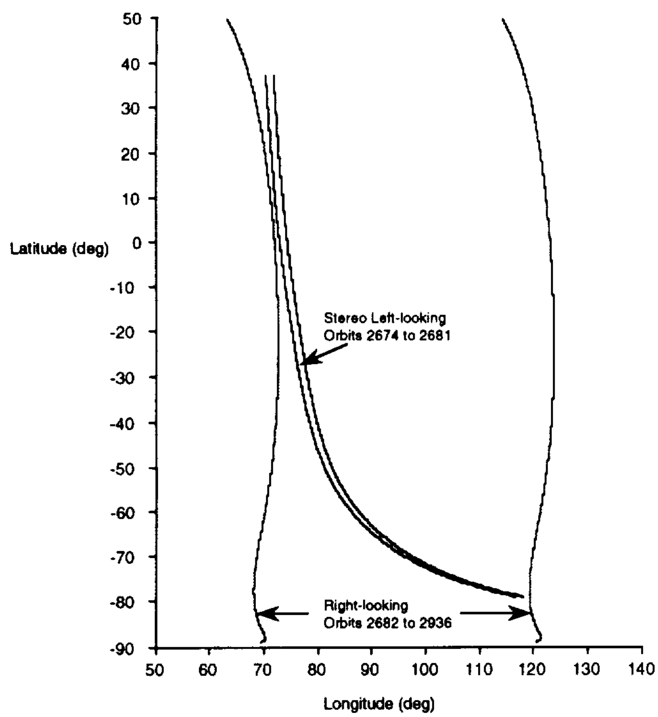

Fig. 11 Stereo experiment orbits 2674 to 2681 and corresponding right-looking coverage, orbits 2682 to 2936.

scheduled to be flown in a thermally hot time frame, which implied the need for hide maneuvers. A side effect of the cooling performed with a hide maneuver is that less time remains in the orbit for mapping and playback of data, so acquiring the range of latitudes necessary for the experiment was difficult. We were severely restricted in placement of this experiment, since our target range of incidence angles for comparison covers some 90 deg of latitude on the planet surface.

The solution to this problem was to concentrate the observation in the southern hemisphere of the planet, from 15°N to 79°S latitude. This selection allowed one sample to be taken at each stereo incidence-angle pair listed in Table 2, as well as meeting sequence timing constraints. Hide times in this period were reduced slightly, and the Magellan Project agreed to accept slightly higher temperature limits of the onboard components for the duration of this upload.

Since data for cycle 1 have to exist for the stereo data to be compared with, the experiment was further complicated by large gaps that had occurred in the cycle-1 data corresponding to the upload window prescribed by our thermal conditions. Two anomalies occurred in this time frame during cycle 1, causing four-orbit gaps to either side of the experiment area.[15] A specific set of eight orbits was chosen, which fit between these gaps with less than an orbit of data on either side to spare.

The stereo special experiment was successfully executed on orbits 2674 to 2681 on July 24, 1991. Orbits 2682 to 2936 swept back far enough so that all of the stereo experiment area was re-imaged in the right-looking mode.

Results

Figure 12 shows data from cycle 1 in column 1 and corresponding stereo experiment data in column 2. (The stereo effect is seen when the images are combined and viewed through stereo viewing glasses.) The terrain height accuracy resolved from the data is extremely high, some 70–100 m. This is a significant improvement from previous studies, which allow for terrain height accuracies in the 1- to 2-km range.

This was the first time that space-borne stereo imaging was performed at a set of incidence angles this low. The stereo image quality was very high, with the visual impression of these stereo images twice as good as photography from space in terms of vertical exaggeration.

This stereo experiment was judged to be a spectacular success by R. Stephen Saunders, the Magellan project scientist. Cycle 3 of the Magellan mission was replanned, based on the results of this experiment, to be dedicated to the collection of stereo data, and we are currently operating with the incidence-angle profile unchanged from the experiment.

Polarimetry Experiment

Duane Muhleman of the California Institute of Technology proposed an experiment to collect data for the study of the emission characteristics of the Venusian surface. In cycle 1, the surface was imaged with a horizontal polarization, i.e., parallel to the surface of Venus. This experiment suggests imaging the surface again, but with the spacecraft rotated 90 deg about the HGA boresight so as to achieve a vertical polarization. These two images are then digitally subtracted from one another to determine a discrete difference in the amount of emission for these two planes of polarization. This difference is a direct function of the dielectric constant of the surface, and this experiment was to provide empirical data on its determination.

Description

The Rhea and Theia mountains, located in the Asteria region in the northern hemisphere of Venus, are areas of strong, multiple scattering properties and an ideal site for such an experiment. The experiment was configured to map this region of the planet with the nominal, cycle 1 incidence-angle profile, but with the spacecraft rotated about the boresight of the HGA, so as to transmit vertically and receive vertical polarization. These data were compared with nominal data taken in cycle 1, transmitted horizontally and received horizontally.

The experiment mapping profile was constructed with a +90 deg roll about the HGA boresight. This was done to collect the desired polarization, as well as to satisfy spacecraft constraints dealing with keeping the star tracker from being pointed directly into the sun. All attitude control parameter predictions appeared to be within tolerances, with the exception of the Y-body startup rate. A rate limit is set for each

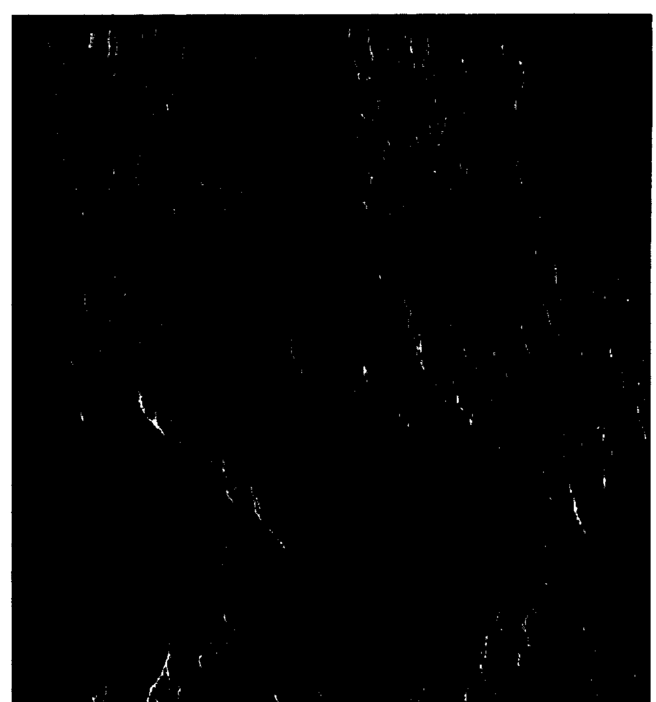

Fig. 12 Column 1 shows data taken during cycle 1 with the left-looking incidence-angle profile, and column 2 shows data taken with the stereo incidence-angle profile.

axis, and predictions for this experiment indicated a minor violation. The purpose for this rate limit is to ensure that the system has sufficiently stabilized so that pointing accuracy can be maintained, as opposed to the potential invocation of fault protection, so this constraint was waived.

Initial predictions of radar performance appeared quite good, with the only significant deviation in performance occurring in the predicted signal-to-ambiguity ratio, which dropped by 3 dB. This was due to an azimuth antenna pattern that is broader than that used for horizontal data collection and was accepted for purposes of this experiment.

Execution

Magellan passed over Rhea and Theia Mons in early December 1991. This was in a thermally constrained time in cycle 2, and the primary goal of the upload was to map areas that were missed in cycle 1 due to reduced mapping from thermal hiding. This primary target area was from 4 to 79°S latitude, whereas the polarimetry targets fell between 23 to 32°N latitude.

Unlike in the stereo experiment, hide times could not be reduced to the point where both the polarimetry target area and the primary target area could be mapped together under normal operating constraints. To this end, the polarimetry experiment orbits were required to be built separately and called from a different portion of spacecraft memory than is normally done. This created issues with regard to orbits being coordinated together, both entering and exiting the polarimetry experiment time, as well as severely restricting the number of orbits that could be allocated to the experiment because of the amount of available spacecraft memory.

The experiment was executed on December 13, 1991, without incident.

Results

In Fig. 13, column 1 shows data collected in cycle 1 in the horizontal polarization; column 2 shows the corresponding data in vertical polarization collected during this experiment; and column 3 shows the SAR backscatter difference between these images. This phenomenon is not well understood, and scientists continue their analysis to explain this unexpected and striking result.

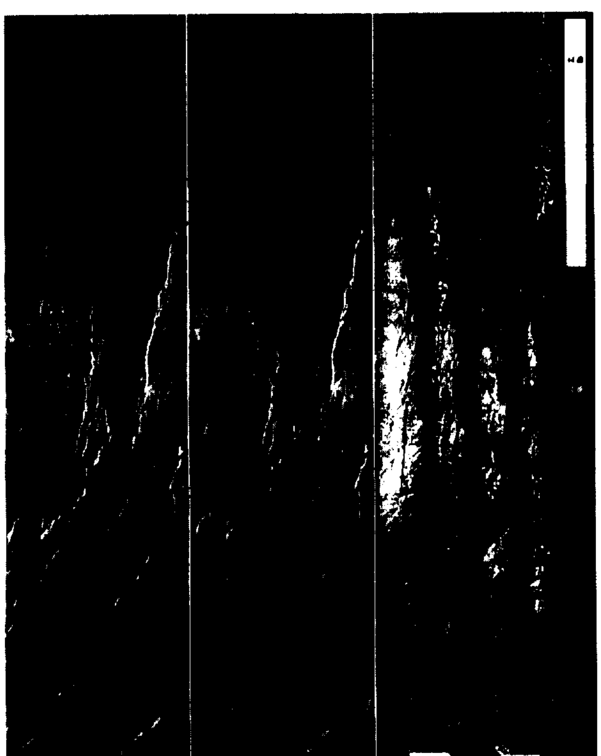

Fig. 13 Column 1 shows four mosaicked orbits of data taken during cycle 1 with horizontal polarization. Column 2 shows four mosaicked orbits of data taken during the experiment with vertical polarization. Column 3 shows the difference in emission.

Maxwell Montes Stereo Experiment

A second stereo experiment was proposed by Gordon Pettengill of the Massachusetts Institute of Technology. This experiment would perform stereo mapping of the Maxwell Montes area, a region within the continent-like feature of Ishtar Terra in the northern hemisphere of Venus. The purpose of this experiment was to build a high-incidence angle stereo map of this geologically interesting region. It was felt that, because of the high reflectivity and the general roughness of this region, mapping with lower-incidence-angle differences would have severe problems with layover effects.

Mapping with this high-incidence-angle profile would also be used to locate the abrupt rise of the southwest face of Maxwell, which contains what may be the highest cliff in the solar system. This rise stands approximately 10 km high and is sufficiently steep that its location cannot be resolved by the onboard altimeter.

A secondary goal of the experiment was the imaging of the Sif and Gula mountains, centered at 25°N latitude near the prime meridian.

Description

This experiment specifically asked to combine the data in the area of Maxwell taken in cycle 1 with a higher incidence-angle profile from 60 to 70°N latitude. The altitude of Magellan over this region of the planet is roughly 1200 km. A higher angle of incidence than what is normally flown in the cycle 1 incidence-angle profile is difficult to maintain in terms of radar performance at such an altitude. A trade study was performed to achieve a reasonable value of angular difference between cycle 1 and this experiment. A value of 7-deg difference was determined to be the nominal value because lower values provide little or no stereo registration, and higher values (13-deg difference would have been optimal from a registration point of view) cause severe degradation in the radar performance. The incidence-angle profile is shown in Fig. 14.

Performance predicts were quite strong, considering the steepness of the incidence angle at this altitude. Several commanding alterations were made to improve performance to this level, including taking one less raw look and lowering the pulse-repetition frequency slightly to improve range ambiguity performance.

Execution

The target area was designated as 60 to 70°N latitude and 350 to 10° longitude, with the cliff being located in the "center" at 64.8°N latitude, 358.5° longitude. This area was effectively swept out by the two-week mapping period that began on January 24, 1992. The Magellan flight team decided to realign upload boundaries to allow for this entire experiment to be flown in a single two-week upload.

This experiment fell in the time frame when apoapsis as seen from Earth is occulted by Venus. This means that, although data are taken normally, they cannot be played back according to the normal strategy, since portions of playback time are obstructed from the receiving stations on Earth. A special commanding strategy is used in this apoapsis occultation time frame, which wraps playback windows in the orbit on either side of the occultation.

A decision was made in early November 1991 to use a reduced hide time of 10 min for this upload. This would allow the entire Maxwell area to be mapped and still fall within the restrictions of occulted mapping. A contingency plan was also recommended, in case the reduced hides caused unexpectedly high temperatures. This was to tailor the mapping attitude

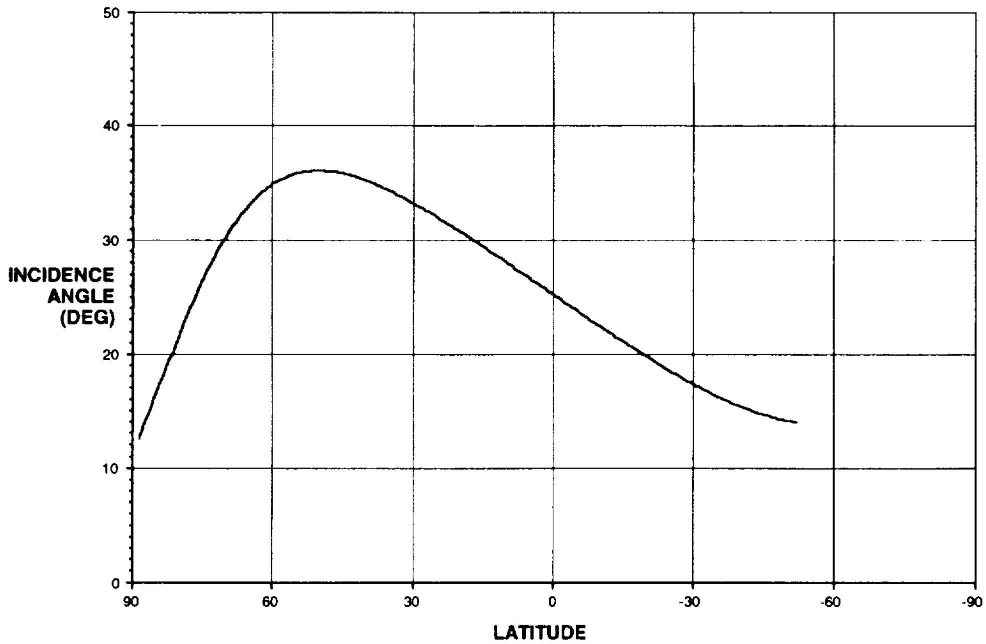

Fig. 14 Maxwell stereo experiment incidence-angle profile.

profile to turn the HGA toward the sun after the Maxwell area was mapped, thereby placing an artificial third hide in the sequence, at the expense of data taken to the south of the Maxwell area.

On January 4, 1992, three weeks before this experiment was scheduled to fly, transmitter A, the primary transmitter used for playback of data, showed a complete loss of data modulation. Within days, it was deduced that this transmitter had failed. Transmitter B, the backup transmitter that was taken off line in March 1991 for a power-grabbing spur, was placed back on-line on January 10, 1992, to attempt to find a mode that could be used to transmit data. The spur in transmitter B reduced power by 6–8 dB and was in a frequency that interfered with nominal Magellan data playback. It was determined in the following three weeks that, by going to a lower data rate playback and a lower transmission frequency, the spur was able to be avoided so that playback could commence.

This reduced playback rate had a severe impact on the data collection strategy that had been planned for the Maxwell experiment. Because less data could be played back due to the lower transmission rate, less data could now be taken. A number of alternatives were considered, and finally a new plan was adopted where data were collected from 18 to 76°N latitude. This allowed sufficient time in the orbit to obtain the observation and to playback the portion of the data corresponding to the Maxwell region, from 60 to 70°N latitude. These reduced timing constraints forced the use of the nominal playback strategy, which caused data collected from 28 to 35°N latitude to be sacrificed. Venus occulted Earth at this time, so these data were forced to be played back into the planet.

Thermally, hides were set in this load not to achieve a minimum temperature but to achieve a minimum temperature variation in the transmitter component. By minimizing the temperature cycle depth, the component was placed under less stress, even though it was operating at a higher temperature.

The experiment was performed from January 24, 1992, to February 7, 1992, without incident.

Results

Although the results of this experiment are still being analyzed, initial examination of the data shows that the interpretability problems caused by layover effects were significantly lessened by this experiment, validating the 7-deg incidence-angle difference.

The Sif and Gula mountains were successfully imaged, just missing the area of data lost due to apoapsis occultation. In the haste of replanning this experiment, however, the Maxwell cliff was not imaged. As data were taken, they were recorded on an onboard, four-track tape recorder. As tracks were switched, small amounts of data were lost, and unfortunately the imaging of the Maxwell cliff occurred during one of these track switches.

Conclusions

Four special radar flight experiments were performed to aid in planning activities in future mission cycles. The experiment in high-resolution imaging showed only secondary improvements and is not planned to be used.

Two experiments in stereo images were performed, with very strong results. Stereo imaging greatly enhances image interpretability and the third cycle of the Magellan mission was replanned based on these experiments to focus on collection of stereo data. Data collection in this mode continued until mid-July 1992.

The experiment in polarimetry revealed a number of interesting and unexplained characteristics of the Venusian surface, and an enthusiastic science community requested a number of future polarimetry observations to aid in characterization of these surface phenomena.

Acknowledgments

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